Simulation modelling and analysis of linkage-controlled traffic scheme in waterway transport key nodes

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Abstract: As global shipping undergoes rapid expansion, pivotal waterway transport systems—including significant nodes like the Panama Canal, the Suez Canal, and the Three Gorges-Gezhouba dams—are increasingly emerging as system-wide bottlenecks that limit transportation capabilities. Recognizing the pressing need for efficient traffic organization at these critical junctures, we designed a hybrid simulation model, which integrates Cellular Automaton and Multi-Agent methods, to analyse traffic efficiency and evaluate different ship organization schemes at these key waterway nodes. The Three Gorges-Gezhouba dams serve as a case study, where we crafted and executed four simulation scenarios that accommodate a range of variables such as different traffic organization schemes, traffic flow volumes, and anchorage capacities. Key operational indicators such as the maximum average waiting time of ships at the anchorage, and the period when the anchorage along the waterway reaches saturation, provide insights into the system's operational condition. The simulation outcomes highlight the proposed model's capability to accurately quantify the impact of implementing a linkage-control scheme and underscore the utility of dynamic adjustment of water area ranges under linkage-control for managing various traffic scenarios. Consequently, our research not only enriches high-precision simulation methodologies but also bolsters decision-making processes concerning ship traffic organization at waterway transport key nodes.

Keywords: Ship traffic organisation; Cellular automaton; Multi-agent; Waterway transport key nodes; Linkage control

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1. Introduction

In Global shipping, waterway transport key nodes (WTKNs) such as the Panama Canal, Suez Canal, Strait of Malacca, and the Three Gorges-Gezhouba dams (TGGD) hold significant strategic and economic value due to their unique geographical positioning. In the wake of the cessation of the COVID-19 pandemic and the accompanying resurgence of the global economy, maritime trade worldwide is undergoing swift expansion.

Due to the surge in transport demand, the Panama Canal has experienced congestion, and the average waiting time for ships has increased from 5 to 6 days to about 10 days, some ships need 9 days to pass through the canal, while the usual time is only about 2 days. In 2021, a container ship named “Ever Given”, which was about 400 metres long and weighed about 200,000 tonnes, ran aground in the canal on March 23, blocking the bi-directional traffic of the Suez Canal and leaving more than 300 ships stranded near the canal for more than a week. As China's most substantial water conservancy project, the TGGD face a significant burden of navigation (Liu et al., 2014). The water region surrounding the TGGD has increasingly seen ships pausing their navigation and waiting due to the constraints of the ship locks' carrying capacity (Zhao et al., 2020). WTKNs are experiencing escalating navigational pressures, progressively morphing into chokepoints that curtail traffic efficiency. In light of this context, it has become a great challenge that how to alleviate the accumulation of ship traffic management pressure resulting from the inevitable imbalance of limited navigational resources and growing traffic demands at WTKNs. Despite the criticality of these areas, a paucity of research exists focusing on ship traffic organisation and management in WTKNs. Under such circumstances, applicable method of navigational efficiency and managing performance analysis become paramount.

There is a lack of appropriate analytical methods and models for the efficiency of navigational and traffic organisation schemes for complex waterway transport systems. These WTKNs, which are jointly constituted by waterways, anchorages, narrow bottlenecks or ship locks, share the same theoretical problems, but need to be modelled and analysed in a way that is specific to the object of study. To address these issues, we have developed an analytical framework and use simulation methods to simulate and analyse the state of the transport system and the effectiveness of the traffic organisation of the WTKNs. The major contributions of this paper are as follows:

(1) The navigational efficiency of ships crossing Waterway Transport Key Nodes (WTKNs) is represented through a robust mathematical model. This model allows for the precise calculation of efficiency indices across various traffic organisation schemes. Additionally, a sophisticated framework has been developed for analysing lock-passing ship traffic organisations. This framework facilitates the detailed calculation and quantification of various levels of saturation and traffic efficiency, enhancing the theoretical understanding of navigable waterways' operational dynamics.

(2) A traffic simulation model using Cellular Automaton (CA) and Multi-Agent methods was developed for WTKNs to offer a nuanced analysis of navigation efficiency and ship delay under various anchoring setups. This model intelligently expands anchorages, allowing for a deeper theoretical exploration into how different anchoring configurations affect traffic flow and delay. The integration of CA and multi-agent systems provides a comprehensive tool for simulating and studying complex interactions and dynamics at critical waterway junctions.

(3) Experiments adopting several scenarios considering different traffic organisation scheme, traffic volume, and anchorage capacity were formed and conducted using the TGGD as a genuine case for examination. The best anchorage adjustment plan and traffic organisation scheme can be chosen through a comparative examination of the outcomes based on the effectiveness of the navigation.

This paper is organised as follows. The pertinent literature on ship traffic organisation and

traffic modelling are reviewed in the second section. The third section elaborates on the research object and problem of the traffic behaviour of ship lockage, and the fourth section presents the quantitative analysis and mathematical expression of the traffic behaviour of ships passing through the TGGD water region. The fifth section proposed a method for simulating a multi-node ship traffic system based on CA and multi-agent theories for the water area of large water conservancy hubs. The simulation experiments and discussions are provided in the sixth section, and conclusions and potential directions for further study are covered in the seventh section.

2. Literature Review

The operation of a traffic system heavily depends on traffic organisation. The traffic organisation plan determines how effectively a traffic system operates. There is little research on the organisation of traffic in the WTKNs. The following related areas were included in the literature review:

2.1 Ship traffic organisation methods

Numerous academics have investigated the best ways to organise and regulate traffic in certain water bodies, such as the San Francisco Bay, the Finland Bay, the Istanbul and Singapore Straits, the Bohai Bay, and the Ningbo Zhoushan Waters (Goerlandt et al., 2011, Montewka et al., 2014). Aydogdu et al. (2012.) suggested a management-oriented strategy for organising ship traffic based on a number of research findings on the Istanbul Strait and in accordance with the spatiotemporal distribution features of traffic flow. Wang and Schonfeld (2007) investigated a method for calculating the profit of canal transportation under the conditions of lock closure and service time modification, integrated the demand elasticity into the simulation model, and optimised the transportation. By fusing AHP and TOPSIS, Shi et al. (2019) created a decision-making model to help enhance the lock's carrying capacity, identified the relevant factors, and prioritised them. Li et al. (2020) provided a comprehensive overview of the applications of traffic bottleneck models in traffic management and proposed potential directions for future research in this area, including the consideration of the impact of autonomous driving and communication technologies on traffic flow efficiency. Based on the traffic bottleneck model, Deng et al. (2021) established a method of moving the service time window to manage lock congestion caused by the uneven distribution of ship traffic demands. Liu et al. (2021a，2021b) proposed a mixed-integer linear programming (MILP) model for integrated planning of berth allocation and ship sequencing in a one-way navigation channel seaport, aiming to minimize the weighted dwelling time of all ships. Ksciuka (2023) et al. reviewed and analysed the uncertainties in maritime transport, finding that uncertainties in port operations are very important for improving the efficiency of transportation. Zhang et al. (2024) explore the ship traffic scheduling problem with uncertain arrival and departure times using a hybrid optimization method. This method combines a memetic algorithm for global exploration with a variable neighbourhood search algorithm, which utilizes problem-specific neighbourhood operators for local search.

It has been discovered that most of the research on waterway traffic organisation and performance assessment has focused on the use of optimisation algorithms and management policies, with simulation methods (Zhang et al., 2008) less frequently applied to the organisation of traffic at WTKNs.

2.2 Ship traffic study in WTKNs

A model developed by Ungo et al. (2012) provides an analysis of the competitive dynamics of the shipping routes through the Panama Canal in comparison with alternative routes, using total transport costs as a basis. Muirhead et al. (2015) developed a scenario-based model using Monte Carlo simulation to explore potential shifts in maritime traffic patterns following the expansion of the Panama Canal. Carse (2012) examined the traffic services and management of the Panama Canal

from the perspective of infrastructure and environment. Pangano et al. (2016) investigated the economic impact of the canal expansion on Panama's maritime industry cluster. Fan et al. (2022) dissected the blockage incident in the Suez Canal in 2021, underscoring the severe implications of such disruptions in WTKNs. Agussurja et al. (2018) optimised modelling under resource constraints tailored to the specific circumstances of the Strait of Singapore, effectively alleviating navigational pressure by reducing traffic density and ship delay. Qu et al. (2012a) proposes a decision tree model to estimate the loss to global economy on the hypothesis of an extreme scenario of blockade of the Straits of Malacca and Singapore. Zhang et al. (2019) harnessed AIS big data to analyse maritime traffic demand and the spatio-temporal dynamics of ship traffic in the Strait of Singapore. Nofandi et al. (2022) utilised the Vessel Traffic Service (VTS) system Fenix to address ship congestion in the Strait of Malacca and the Strait of Singapore, optimising both traffic safety and efficiency. It can be found that the research on traffic organisation and efficiency assessment methods for WTKNs still needs further improvement.

2.3 Traffic simulation model

Waterway traffic simulation has a long history, and the original models were generally based on rules, queueing model and Arene software, etc. Köse et al. (2003) conducted a simulation of the Istanbul Strait under distinct traffic conditions, analyzing the outcomes and exploring the potential effects of an anticipated rise in marine traffic resulting from new oil pipelines. Mavrakis et al. (2008) presents a queuing model for maritime traffic in the crowded and challenging Bosporus Straits, considering its physical characteristics and maritime regulations. Almaz et al. (2012) presents a simulation model for vessel traffic in Delaware River, studyed the impact of deepening on navigational efficiency, port performance measures, and risk analysis. Rahimikelarijani et al. (2018) concentrate on simulating and analyzing vessel traffic and operations in the Houston Ship Channel. They employ a discrete event model in Arena to evaluate various closure scenarios using real-world data.

The application of CA in transportation first appeared in road traffic and is currently one of the most widely used models. The Wolfram model (e.g., Wolfram et al., 1983, 1984a, 1984b), Nagel–Schrechenberg (NaSch) model (Nagel and Schreckenberg, 1992), BML model (Biham et al., 1992), and other traditional CA traffic flow models are a few examples. Researchers mostly study the effects of slow-start, acceleration, and deceleration, followed by traffic, when using the single-lane model. Ren et al. (2016) constructed a linear motion model to describe the non-uniform bicycle traffic at signalised junctions and examine the impact of the dispersion phenomena on the effectiveness of bicycle passing. By simulating vehicle characteristics and intertemporal distances, Ruan et al. (2017) created a simulation model to precisely compute traffic loads on infrastructure, such as bridges. To demonstrate how a reverse left-turn lane can increase the capacity of intersections to pass through traffic, Chen et al. (2019) built a simulation model that can simulate vehicles turning left at crossings. Sun et al. (2023) built a simulation model based on the driving differences between human-driven cars and self-driving cars, and analysed the impact of trust level on traffic efficiency from two perspectives: efficiency and safety.

The CA model has been used extensively in simulations of ship traffic flow. In the original model, the speed of the ship remained constant during voyage, and the speed of each ship in the channel was similar (Liu et al., 2010). After an improvement, the ship's speed in the model is set according to the type of a ship, and it then increases or decreases in accordance with the ship's subsequent behaviour (Blokus et al., 2014). Researchers have incorporated random variables into the automata model in the simulation of ship traffic flow to capture the impact of environmental factors on ship movements (e.g., Qi et al., 2017a, 2017b, Qu et al., 2012b). Studies on the effects of lane switching on traffic efficiency have also been conducted due to the approach channel's increased bustle (e.g. Sun et al., 2015, Hu et al., 2017, Qi et al., 2021).Feng (2013) proposed a model

considering channel narrowing near the bridge area and examined the impact of the warning zone's length and ship arrival pattern on the channel's transit capacity.

The demand for the precision of ship traffic simulation has likewise increased as computer technology has advanced. The functionality of the simulation model has been further enhanced by the addition of more traffic agents. Similarly, the use of multi-agent simulation technology in the field of transportation is expanding rapidly (e.g., Zhang et al., 2005, Vaněk et al., 2011, 2013). Examples include the MATES model (Fujii et al., 2017) based on a multi-agent framework, the microscopic model of an intersection (Karaaslan et al., 2018), and the model of an urban macroscopic road network (Souza et al., 2019). A simulation model that combines CA and multi-agent systems has been developed. By incorporating a multi-agent structure into a continuous CA model, Yeldan et al. (2012) investigated the impact of driver and vehicle heterogeneity on traffic. Deo et al. (2014) studied the impact of various vehicle types on traffic using one-way single-lane intersection and two-way two-lane T-intersection models. Based on multi-agent technology, Vranken et al. (2021) investigated the impact of the share of autonomous vehicles on road capacity. Zhao et al. (2018) studied intersection conflict and congestion in a scenario with automated driving using a CA model. Małecki (2018) established a mixed traffic model that included roadways and parking lots using CA and multi-agents, and they studied the impact of traffic flow, speed, and trip duration in the research areas on drivers' behaviours. To study the traffic efficiency of road intersections under various traffic strategies, Wang et al. (2021) developed a simulation model based on CA and multi-agents, combining the high efficiency of CA with the capability of multi-agents to simulate complex elements. Zhang et al. (2022) established a model combining discrete event simulation and multi-agent model to study the maximum navigation capacity of the Three Gorges dam under the new traffic organization scheme. Liu et al. (2024) developed a heterogeneous traffic flow simulation model based on CA that coexists autonomous and manned ships.

Waterway traffic simulation techniques based on CA and multi-agent systems have also been introduced. Using an agent to define the features and autonomous behaviours of each ship. Jiang et al. (2019) developed a combined CA and multi-agent simulation model based on ship behaviour, which confirmed the significant influence of ship behaviour on port operations. In a similar vein, Liu et al. (2021) employed CA and multi-agent simulation techniques to create a simulation model that emulates the arrival and departure of the Liquefied Natural Gas (LNG) carriers at ports. By comparing various traffic organization schemes, they evaluated the navigation and port operation efficiency of the LNG carriers in the simulation.

In summary, it becomes evident that there is a relative scarcity of research concerning the traffic organisation and efficiency evaluation pertaining to WTKNs. Moreover, there is a conspicuous absence of methodologies utilising simulation models from the perspective of ship traffic flow. The accuracy and adaptability of existing methods necessitate further enhancement.

3 Problem statement

3.1 Presentation of WTKNs

WTKNs consist of critical infrastructures that support global or domestic maritime transportation. They primarily encompass the Panama Canal, the Suez Canal, and the TGGD. Each of these structures comprises several key components.

Anchorages, for instance, are crucial areas within the WTKNs where ships can safely wait before transiting or while dealing with administrative procedures. The fairways, or navigational channels, are designated routes marked with aids to navigation, allowing safe passage of ships.

Ship locks, which play a critical role in these structures, particularly in the Panama Canal and the TGGD, enabling ships to navigate through different water levels by raising or lowering the water level within the lock. They essentially serve as water elevators for ships.

Constricted sections or narrow passages in the fairways, such as those found in the Suez Canal and the Strait of Malacca, pose particular navigational challenges, requiring skilled pilots and strict traffic regulation to ensure safety.

Finally, each of these components is bound by a complex system of traffic scheme and procedures designed to ensure smooth and efficient transit while maintaining safety and environmental standards. Together, these parts contribute to the unique and vital role that WTKNs play in maritime transport, as shown in Fig. 1.

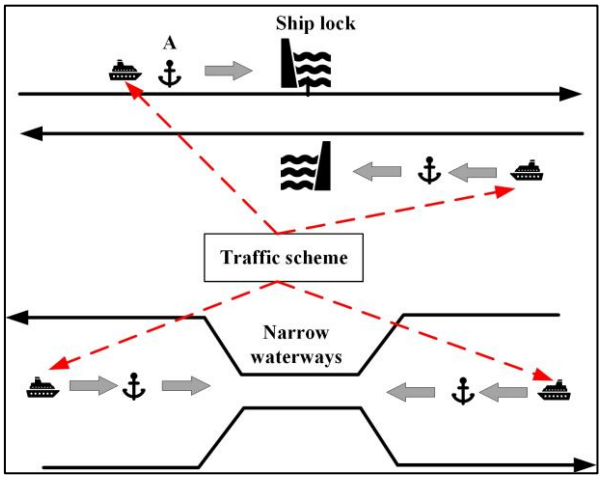


Fig. 1. Structure of WTKNs

The carrying capacity of WTKNs is inherently limited by physical constraints. Key among these are narrow passages in the navigational channels and the presence of locks. Narrow passages or constrictions present particular challenges. They require meticulous navigation and often can only accommodate one-way traffic, leading to scheduling constraints and potential delays. Meanwhile, locks, which are used to elevate or lower ships between different water levels, have a limited capacity and necessitate time for filling and emptying, thus creating a bottleneck in the system. When navigational demand outstrips the limited capacity of these key nodes, it results in a backlog of ships, often causing them to anchor and wait their turn for transit. This situation can lead to considerable delays, disrupting shipping schedules and impacting the efficiency of global maritime trade. Therefore, the management and scheme of these constraints is crucial to maintain the fluidity of traffic and minimise waiting times at these vital junctions in the world's maritime network.

3.2 Ship traffic organisation

For WTKNs, the traffic organisation schemes typically implemented are often relatively straightforward, usually adhering to a first-come-first-served principle. This entails that ships arriving first pass through locks or channel narrows ahead of those arriving later. However, there are also more specialised scheduling methods in place. For instance, the TGGD implemented a linkage control method for ship organisation and scheduling in 2018. What follows is a comparison of ship traffic patterns at the TGGD before and after the introduction of this linked control scheme.

Before implementing the linkage control scheme, both upstream and downstream ships must find a place to anchor close to the dam, wait for the ships in front of them to pass, and then line up to enter the ship lock, as shown in **Fig. 2**. However, owing to the rapid development of the Yangtze River shipping industry, there is a high demand for ships to pass through the Three Gorges Dam. Consequently, many ships wait at the anchorage close to the dam because of the limited carrying capacity of the Three Gorges Ship Locks and the high need for ships to pass through the ship lock. The number of ships that need to berth cannot be accommodated by the anchorage capacity.

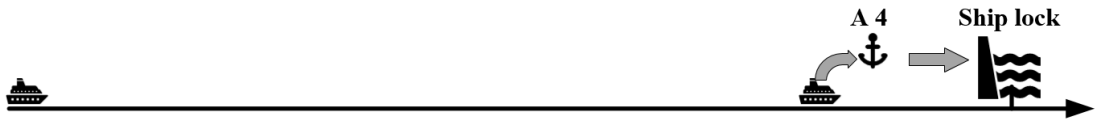


Fig. 2. Schematic of ships passing through a lock.

The linkage control scheme for ships passing the dam has been in effect since 2018 according to the Yangtze River Navigation Administration, as shown in **Fig. 3**. The main goal of the scheme is to arrange these ships in anchorages and waiting areas along the ships' routes in the order and locations specified in the navigation plan submitted to the responsible department by ships passing through the Three Gorges dam and gradually despatch the ships to be locked to the core waters in accordance with the operational efficiency of the Three Gorges dam waterway transportation system.

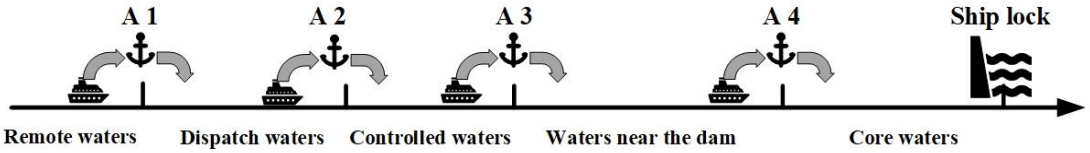


Fig. 3. Schematic of a Ship Passing a Lock after Implementing Linkage Control.

3.3 The Three Gorges-Gezhouba Dams

Given the complexity and representativeness of the navigation system composed of the TGGD and its upstream and downstream waters, this study addresses the organization and effectiveness of traffic at WTKNs from the perspective of ship traffic flow. Mathematical models were introduced to establish a traffic analysis framework capable of assessing the efficiency of ship traffic and the degree of anchorage saturation.

The Yangtze River has developed into the busiest inland river in the world over a long period. According to statistics, more than 3.5 billion tons of cargo was transported via ports along the Yangtze River trunk line in 2021.[1] As the shipping industry of the Yangtze River has grown, the traffic efficiency in the area has deteriorated. Owing to limitations in the carrying capacity of navigation infrastructure, ships in the TGGD water region have become accustomed to stopping and waiting for locks to open in recent years. The TGGD as the transport key node of Yangtze River, it's lack of sufficient carrying capacity has limited shipping along the Yangtze River.

The main body of the Three Gorges dam is composed of a concrete gravity dam, a flood release gate, a hydropower plant behind an embankment, a permanent fifth-class ship lock, and a ship lift, which are the hub's navigation areas. The other major components are structures associated with power generation and navigation. The Gezhouba dam, which is 38 km downstream of the Three Gorges dam, consists of a ship lock, a power plant, a sluice gate, a scouring sluice, and water-holding structures. A fleet can pass through the 1st and 2nd ship locks with a load between 12000 and 16000 tonnes at a time because the locks have an effective length of 280 m, a net width of 34 m, and a length of 280 m**.** At the Three Gorges Dam, south lock and ship lift can be used for downstream ships, and north lock and ship lift can be used for upstream ships. At the Gezhouba Dam, all three locks can be used by both upstream and downstream ships (**Fig. 4**).

[1] http://www.gov.cn/xinwen/2021-12/31/content_5665919.htm

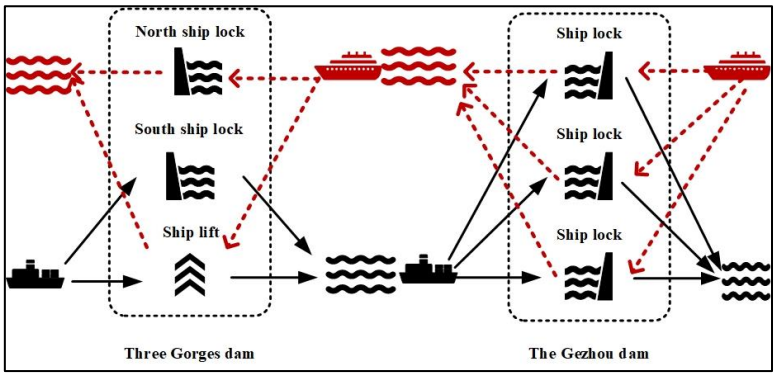


Fig. 4. Structure of the ship locks.

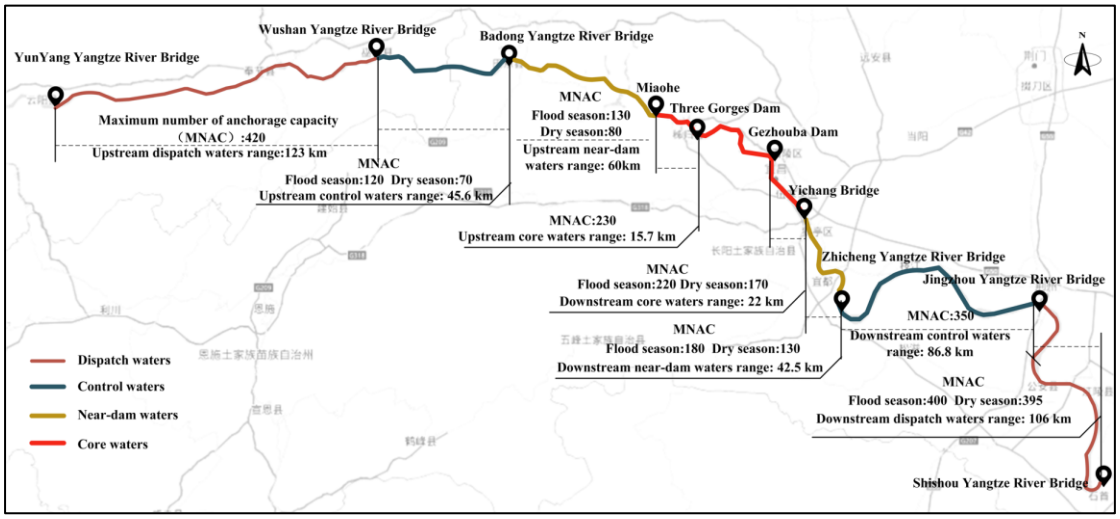


Fig. 5. Linkage control water area.

(1) Division of water areas

Linkage-controlled water area is divided into five areas based on its proximity to the Three Gorges dam: the core waters, near-dam waters, control waters, dispatch waters, and remote waters (**Fig. 5**).

1. Core waters: the waters in the middle reaches of the Yangtze River between the Yichang Yangtze River Highway Bridge (610.8 km in the middle reaches) and the Miaohe River (62.5 km in the upper reaches).

2. Near-dam waters: the waters between the Miaohe River and the Badong Yangtze River Bridge in the upper reaches of the Yangtze River (122.4 km in the upper reaches) and the waters between the Zhicheng Yangtze River Bridge and the Yichang Yangtze River Highway Bridge in the middle reaches of the Yangtze River (568.3 km in the middle reaches).

3. Control waters: the waters in the upper parts of the Yangtze River, between the Badong Yangtze River Bridge and the Wushan Yangtze River Bridge (168.0 km) and between the Jingzhou Yangtze River Bridge (481.5 km in the middle reaches) and the Zhicheng Yangtze River Bridge (481.5 km in the middle reaches).

4. Dispatch waters: the water area between the Wushan Yangtze River Bridge in the upper reaches and the Yunyang Yangtze River Bridge in the upper reaches and the water region between the Shishou Yangtze River Bridge in the middle reaches (375.5 km in the middle reaches) and the Jingzhou Yangtze River Bridge (291.3 km in the upper reaches).

5. Remote waters: the waters above the Yunyang Yangtze River Bridge and the waters below the Shishou Yangtze River Bridge on the Yangtze River's main trunk line.

3.4 Problem statement

(1) The TGGD water region is where ships often stop to wait for the lock according to the original traffic management plan. The capacity of the anchorage in the water region close to the dam cannot accommodate the demand for ship anchoring because of the steadily growing number of ships waiting for the lock, leading to a significant backlog of ships, channel congestion, scheduling issues, and other issues. Currently, it lacks a simulation model to test and verify the navigational effectiveness and traffic status of ships travelling through the dams under various traffic organisation schemes.

(2) The anchoring pressure in the water area close to the Three Gorges Dam has been significantly eased by traffic organisation, which has also significantly reduced congestion. A competent authority must dynamically adjust the number of anchorage and berthing areas along the route in the Linkage control water area because the anchorage and berthing areas along the Yunyang-Shishou water area are greatly affected by the change in water level in the wet and dry seasons. The width of the river surface in the wet season is greater than that in the dry season, and the depth of the anchorage and the area of the anchorage vary with the change in water level.

4. Efficiency quantification and modelling of ship traffic system

4.1 Configuration and definition

Under the new traffic organisation plan, ships must determine their next course of action based on the operational state of the navigation system. The functionality of the ship lock and the margin of anchoring along the way are the two key components of the system status. The ships sequentially berth at the anchorage along their routes because the system's continuous operation prevents the operational efficiency of the ship lock from meeting the needs of the ships going through the lock. Subsequent ships must dock at the anchorage further away from the ship lock when the anchorage closest to the ship lock is complete. We defined the parameters used to simplify modelling and computation, as shown in Table 1.

Table1

Parameter setting.

Classification	*Variable*	*Definition*
Three Gorges-Gezhouba navigation system	$A_d,\ A_c,\ A_{nd}$	Anchorage in dispatch waters, control waters, near-dam waters
	$\|A_n\|$	Anchorage capacity of anchorage n
	$A_{s,n}$	Moored ship quantity in anchorage n
	SL_{TG}	Ship lock in Three Gorges dam
	SL_G	Ship lock in Gezhouba dam
Ship dynamic system	S	Ship passing the ship lock
	$s_{t,l}$	State of ship s ,include time t and location l
	$\|S\|$	The number of ships passing the ship lock
Linkage control	M	Optional action set provided to the ship
	$m_{s,l}$	Action taken by ship s at location l
	P	Dispatch plan
	P_s	Dispatch plan of ship s
	U	Efficiency of navigation system
	T_a	Anchorage service level
	T_s	Saturation time of anchorage

4.2 Navigation efficiency quantification methods

In this study, we use s to represent ships, set the collection of ships as S, and use $|S|$ to

indicate the number of ships in lockage in accordance with the general method of ship lockage. In Eq. (1), P stands for the dispatching plan, which includes plan P carried out by ships when they are in motion, according to ship behaviour M. Location l and time t reflect the ship's state, whereas A stands for the anchorage, a_s stands for the capacity of A, $\overline{a_s}$ represents the number of ships berthed in the anchorage.

$$\begin{aligned} m_{s,l} &= (t_{s,start}, l_s, t_{s,end}) \\ s_i &= (t, l), \ \ i = 1,2,3,\cdots,|S| \\ P_s &= \{m_{s,A_d}, m_{s,A_c}, m_{s,A_{nd}}\} \end{aligned} \tag{1}$$

The traffic efficiency of the TGGD U was altered as a result of the new traffic organisation scheme; however, new indicators and associated methodologies are required to assess the impact of the scheme's implementation. Consequently, in Eq. (2), we select the time T_a at which the anchorage reaches saturation, and the average waiting time T_s of the ship at each anchorage along the route. These two new indicators are used to assess the effectiveness of the navigation system and determine ways of improving the new traffic management plan based on changes in these two indicators.

$$U = (T_a, T_s) \tag{2}$$

In Eq. (3), T_a is a thorough indicator that can show the anchorage's service status along a route and the overall operating status of the navigation system, as seen from the anchorage. The longer the ship is waiting at the anchorage and the more serious the overall delay of the ship, the larger the value of T_a.

$$T_a = \frac{\sum_1^{|S|} t_{end,s}^a - t_{start,s}^a}{|S|} \tag{3}$$

In Eq. (4), T_s can be used to gauge the effectiveness of traffic-management strategies. The anchorage is likely to become saturated if the number of ships entering the anchorage increases faster than the rate at which they depart for the next anchorage. The anchoring approaches saturation later, and the system as a whole does so as T_s increases in value.

$$T_s = t_{end,s}^a, \quad \overline{a_s} = a_s \tag{4}$$

4.3 Modelling based on CA and multi-agent

T_a and T_s are indicators of how effectively ships navigate; it is, therefore, important to mimic the actual ship traffic flow during simulation. The entire complicated system can be reflected in and described using CA and multi-agent systems. For a multi-agent system, communication and coordination among agents are completed through a higher-level coordinator. By receiving instructions from the coordinator, agents make judgments according to their own knowledge base and characteristics and decide their own motion state. Although CA can greatly increase the simulation speed through the calculation mode of spatial-temporal discretisation and the running logic of synchronous calculation, it is challenging to simulate the interaction between traffic individuals and traffic facilities. Communication consumes a significant amount of system time and resources during the system operation. Given that the ship's motion state is updated through changes in cell state, and considering the advantages of the NaSch CA model - simplicity, ease of implementation, and effectiveness in describing traffic flow processes - we adopt the classical NaSch CA model as the foundation for this study. The cells representing the anchorage in the traffic system are expanded and improved, giving them the characteristics of agents that allow them to calculate their own service and despatch states. The operating logic of the synchronous computation of the CA is still used for the entire system, which means that every traffic entity's motion state is updated in the subsequent cycle to satisfy the simulation criteria for both speed and accuracy.

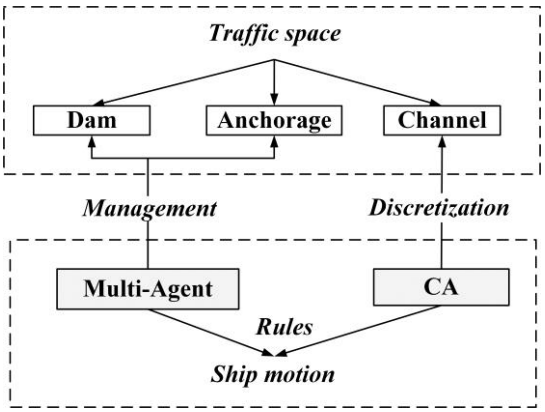


Fig. 6. Structure of the model.

Inspired by the linkage control scheme, a simulation model based on CA and multi-agents is developed to simulate a large-scale navigation system composed of the TGGD and its upstream and downstream navigable waters, as shown in **Fig. 6**. Studying the effectiveness of navigation and ship delays under various traffic organisation schemes can help create groundwork for improving traffic organisation.

An interactive particle system can be considered the behavioural logic of a multi-agent system. The calculation amount of the agent model is greater than that of CA because it is important to establish which agents an agent must interact with in the ongoing process. The simulation system is expanded by leveraging agent thinking, and the anchorage and mooring areas are considered essential nodes. The computation method for the anchorage agent is as follows:

a. Local environment sensing/neighbourhood sensing: collecting the state of the adjacent space ships (cells) with the scheduling process of the control centre.

b. Make decisions and make the next scheduling plan for the anchorage.

c. Execute the scheduling plan and pass the information to the next node.

The agent needs to perceive the ship state and its own capacity in the surrounding cell space at each moment and make scheduling decisions according to the overall scheduling rules of the coordinating controller. As a result, the computational resources required for steps a and b are large. One of the effective ways to improve the efficiency of local neighbourhood perception in a general agent system is to arrange the agent positions in space in a certain way to achieve a ‘regular’/ ‘ordered’ state. The continuous spatial organisation of the CA model can structurally improve the neighbourhood search and perception speed of the agent system. **Fig. 7** shows the agent structure.

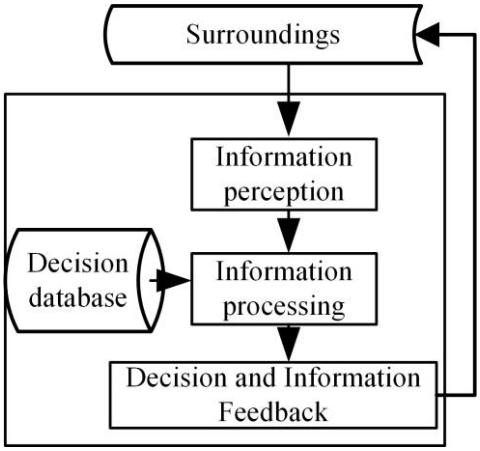


Fig. 7. Structure of an agent.

5. Ship traffic simulation approach

5.1 Spatial-temporal discretisation

In terms of time discretisation, scholars generally set the simulation time step in minutes in water traffic simulations because ships have larger scales and slower sailing speeds compared to vehicles. In the traffic model based on CA, the traffic space needs to be discretised, and it is generally believed that the way a ship occupies a cell is the most efficient one. In the ship traffic model, the safe distance between the same two ships d_{safe} ($d_{safe} = x_{n+1}(t) - x_n(t)$) must be considered. In two-dimensional cell space, the position of the ship is represented by $x(i,j)$, where i represents the lateral position, and j represents the position of the cell located in the channel. As the ship speed is in knots and the time step is in minutes, the cell size is set to 100 m × 100 m in this model to reduce the computational intensity of the calculation, as shown in **Fig. 8**.

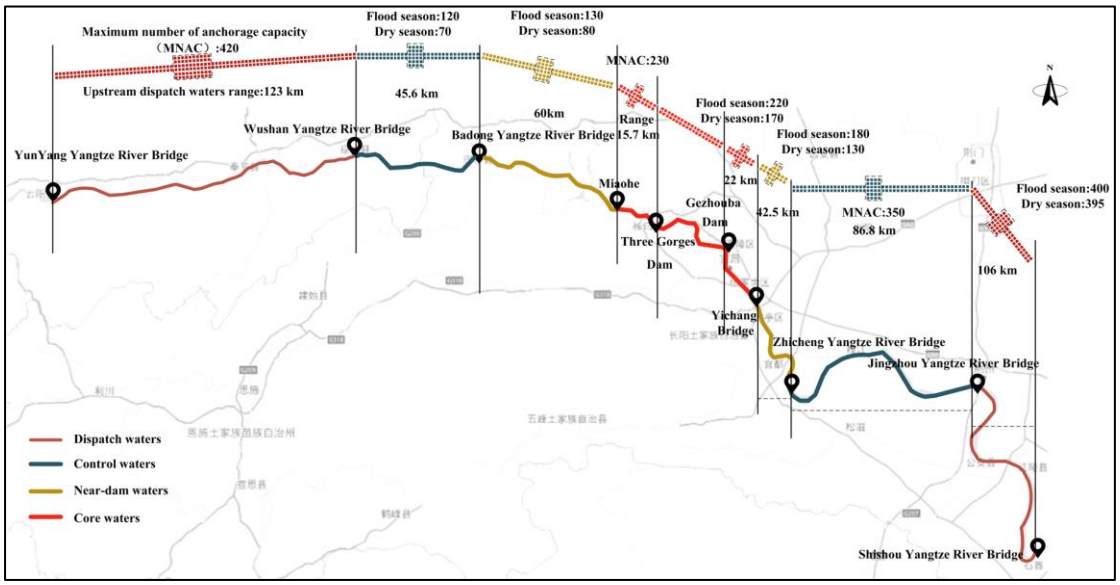


Fig. 8. Schematic representation of the structure of the model discretization.

5.2 Update rules

In this model, the ship movement rules are designed based on the NaSch rules and the characteristics of ship traffic flow.

(1) Acceleration rules:

During normal navigation, if the distance between the front and rear ships is greater than the preset safe distance, $x_{n+1}(t) - x_n(t) > d_{safe,}$ the rear ship will not be affected by the front ship. If the ship does not reach the maximum speed $v_n < v_{max}$, the ship will accelerate (Eq. (5)).

$$v_n \to min\{v_n(t) + 1, v_{max}\} \tag{5}$$

(2) Deceleration rules

When the distance between $ship_n$ and $ship_{n+1}$ is less than the preset safe distance, $x_{n+1} - x_n < d_{safe,}$ the rear ship needs to slow down (Eq. (6)).

$$v_n \to min\{v_n(t) - 1, v_{min}\} \tag{6}$$

(3) Random slow

When a ship is sailing, it will inevitably be affected by wind, water currents, and visibility, which will reduce its speed. Therefore, it is necessary to add a random slowing variable a_Δ to the ship motion rules, and the value is determined according to the natural conditions in the channel (Eq. (7)).

$$v_n(t) = v_n(t-1) - a_\Delta \tag{7}$$

(4) Location update rules

The ship's location update follows the rules shown in Eq. (8).

$$x_n(t+1) = x_n(t) + v_n(t) \quad (8)$$

(5) Changing lanes and overtaking rules

First, the motivation for lane change is judged according to the sorting of the scheme of the front and rear ships and the sailing status of the front and rear ships. Generally, a normal sailing rear ship will not overtake the front ship, but when the crossing plan of the rear ship precedes that of the front ship i, $P_n < P_{n+1}$, the rear ship needs to change lanes, accelerate, and then overtake the front ship.

Second, we determine the lane-changing conditions. If the speed of the front ship is lower than that of the rear ship, $V_n(t) < V_{n+1}(t)$, and there is sufficient space in the adjacent channel, the lanes are changed. After changing lanes, the rear ship needs to speed up to overtake the front ship. When the distance between the front and rear ships reaches a safe distance that needs to be maintained, $ship_{n+1}$ needs to turn into the original channel. The following rules should be followed during overtaking:

Changing lanes rules are as shown in Eq. (9).

$$\begin{aligned} x_{n+1}(t) &= (t,1) \\ x_{n+1}(t+1) &= (t,2) \end{aligned} \quad (9)$$

Acceleration rules are as shown in Eq. (10).

$$v_{n+1}(t+\triangle t) = v_{n+1}(t) - a \triangle t \quad (10)$$

Return to the original channel rules are as shown in Eq. (11).

$$\begin{aligned} &x_{n+1}(t+\triangle t) - x_n(t+\triangle t) > d_{safe} \\ &x_{n+1}(t+\triangle t+1) = (t+\triangle t+1,1) \end{aligned} \quad (11)$$

(6) Anchorage status change rules

The status of the anchorage can be represented by a binary variable. If there is at least one free anchor, the variable is 1; if there is no free anchor, the variable is 0, as shown in Eq. (12).

$$S_{A_x,t} = \begin{cases} 1 & \text{if } \sum A_{x,t} < C_x \\ 0 & \text{if } \sum A_{x,t} = C_x \end{cases} \quad (12)$$

$S_{A_x,t}$ represents the status of anchorage A_x at time t ($x = d, c \ or \ nd$), $A_{x,t}$ represents the occupancy status vector of anchorage A_x at time t, and C_x is the total capacity of anchorage A_x.

When a ship enters the anchorage A_x, it can be expressed as Eq. (13)

$$F_{x,t+1} = \begin{cases} F_{x,t} - 1 & \text{if } F_{x,t} > 0 \\ F_{x,t} & \text{if } F_{x,t} = 0 \end{cases} \quad (13)$$

$A_{x,t}[i] = 1$ represents that the anchor i is occupied, $A_{x,t}[i] = 0$ represents that the anchor i is free, and $F_{x,t}$ is the anchor idle counter.

The update of anchorage status $S_{A_x,t}$ can be expressed as Eq. (14)

$$S_{A_x,t+1} = \begin{cases} 1 & \text{if } F_{x,t+1} > 0 \\ 0 & \text{if } F_{x,t+1} = 0 \end{cases} \quad (14)$$

When a ship leaves the anchorage A_x, it can be expressed as Eq. (15)

$$F\_\{x, t+1\} = F\_\{x, t\} + 1 \quad (15)$$

The update of anchorage status $S_{A_x,t}$ can be expressed as Eq. (16)

$$S_{A_x,t+1} = 1 \quad (16)$$

5.3 Anchorage model based on multi-agents

To meet the requirement of anchorage simulation in the model, the homogeneity of the CA at key nodes is improved, and the cells and their states are expanded. The cells in the same cell space are classified, and the channel cells are still updated according to the basic rules, whereas the anchorage cells have their own unique cell states, neighbours, and rules. To ensure that these different states, neighbours, and rules still coordinate the same function as the whole system, we can regard the cells representing the anchorage as separate individuals, package these cells and states

separately, and expand them into autonomous agents, with cell states as their attributes, so that different types of cells can act on the same cell space harmoniously.

In the actual process of a ship passing the lock, the Three Gorges Navigation Administration is responsible for the entire ship scheduling plan, and the Maritime Safety Administration along the ship's route is responsible for ship scheduling according to the site, as shown in **Fig. 9**.

(1) Remote declaration

After a ship is generated according to the ship generation rules, it is necessary to report the ship's passing plan to the Three Gorges Navigation Administration. The upstream and downstream ship reporting lines are the Shishou Yangtze River Bridge and the Yunyang Yangtze River Bridge, respectively. The time when ships go up through the Shishou Yangtze River Bridge or down through the Yunyang Yangtze River Bridge is the sequencing basis for making crossing plans. Ships are classified and sorted as dangerous goods, container, and commercial automobile transport ships, and a database of ship positions and statuses is established (Eq. (12)).

$$S = \begin{bmatrix} s_1 = (l,t) \\ s_2 \\ \vdots \\ s_i \\ s_{i+1,} \\ \vdots \\ s_{|S|} \end{bmatrix} \tag{12}$$

The scheduling plan of all ships can be expressed as P_S shown in Eq. (13).

$$P_S = \begin{bmatrix} P_1 = \{m_{1,A_d}, m_{1,A_c}, m_{1,A_{nd}}\} \\ P_2 \\ \vdots \\ P_s \\ P_{s+1} \\ \vdots \\ P_{|S|} \end{bmatrix} \tag{13}$$

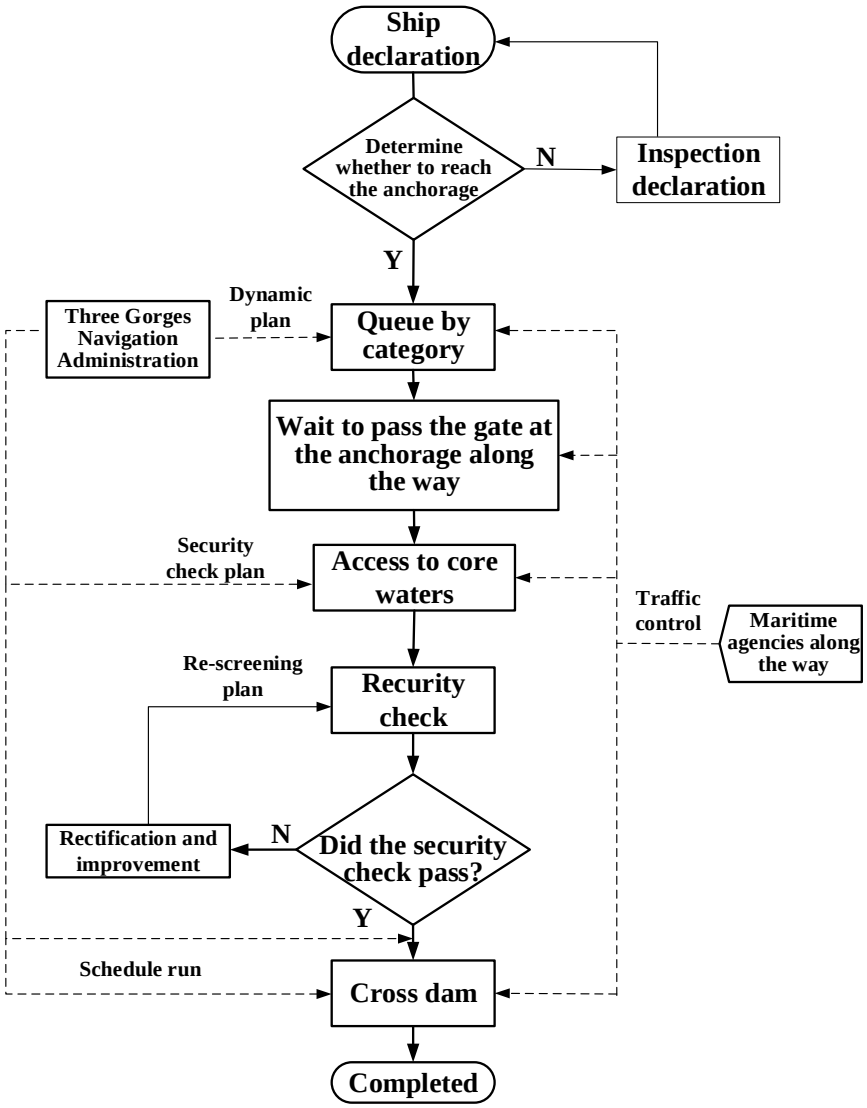


Fig. 9. Traffic organisation flowchart of a ship passing a ship lock.

(2) Scheduling along line

After a ship arrives at the anchorage along its route, it is necessary to update the ship status database based on its position and status (Eq. (14)). The Maritime Safety Administration along its route will reorder and release the anchored ships on the spot according to the ship sequencing plan issued by the Three Gorges Navigation Administration. To achieve this goal, it is necessary to compare the state database with the sequencing plan and establish a new scheduling plan.

$$A_{s,n} = \begin{bmatrix} s_i\left(l_{A_n}, t\right) \\ \vdots \\ s_{i+x}\left(l_{A_n}, t\right) \\ \vdots \end{bmatrix} \tag{14}$$

(3) Security inspection of the water near the dam

A safety inspection is required when ships reach the water near the dam. Qualified ships will continue to wait in line, and unqualified ships will need to return to nearby anchorages for rectification (Eq. (15)). Only after passing the inspection can they continue to queue to pass the ship lock. Decision-making and perception libraries are established in the agent model to realise this process.

$$A_{s,c} = \begin{bmatrix} s_i(l_{A_c}, t) \\ \vdots \\ s_{i+x}(l_{A_c}, t) \\ \vdots \end{bmatrix} + \begin{bmatrix} s_{d,1}(l_L, t) \\ \vdots \\ s_{d,|D|}(l_L, t) \\ \vdots \end{bmatrix}$$

$$P_S = \begin{bmatrix} P_1 = \{m_{1,A_d}, m_{1,A_c}, m_{1,A_{nd}}\} \\ P_2 \\ \vdots \\ P_i \\ P_{i+1} \\ \vdots \\ P_{s_{d,1}} \\ P_{s_{d,|D|}} \\ \vdots \\ P_{|S|} \end{bmatrix} \quad (15)$$

6. Experiment and results

6.1 Traffic flow characteristic analysis

In this study, the data of ships that passed through the TGGD in 2018 are analysed, and the characteristics of ship traffic flow required for simulation are obtained from the data, including ship type distribution, ship length distribution, and ship speed distribution.

(1) Distribution of ship types

From the statistical data of ship traffic flow, it is found that the ships that passing through the linkage-controlled water mainly include bulk carriers, general cargo ships, general dry cargo ships, multipurpose ships, oil tankers, and chemical tankers. From the perspective of ship characteristics, bulk carriers, general cargo ships, and general dry cargo ships can be regarded as cargo ships. Therefore, four main ship types were selected in this study: container ships, dangerous goods ships, passenger ships, and cargo ships, as shown in **Fig. 10**. Their specific generation rules refer to the actual statistical distribution of ship types in 2018.

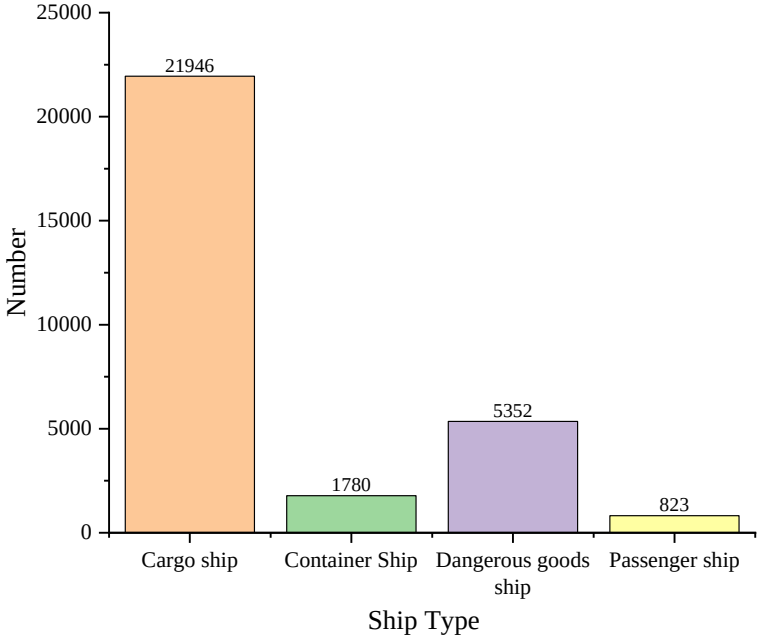


Fig. 10. Distribution of ship types.

(2) Distribution of ship length

By analysing the ship scale, it can be found that the length of ships in the waters controlled by

linkage is mostly between 60 and 140 metres, of which 80–100 m ships account for 48.4%, as shown in **Fig. 11**. Therefore, when ships are generated in the simulation system, the ship length distribution obeys a normal distribution, with an R-square of 0.98 and a standard deviation of 22.6.

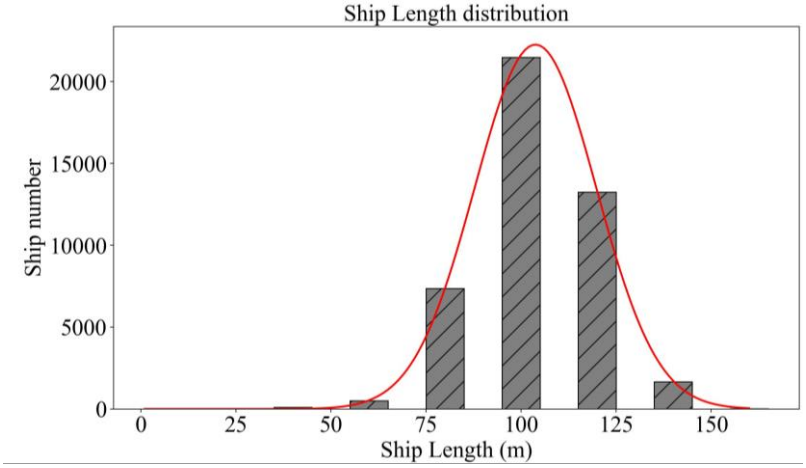


Fig. 11. Distribution of ship length.

(3) Distribution of ship speed

Ship speed distribution refers to the speed distribution range and patterns of all ships sailing in a certain water area. The ship's speed distribution is affected by the navigation environment and the ship's own attributes, but the ship speed mostly obeys a normal distribution.

$$f(v) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(v-\mu)^2}{2\sigma^2}} \tag{16}$$

where $f(v)$ represents the probability that the ship speed is v, σ represents the standard deviation of the ship speed in the water, and μ represents the average speed of the ship in the water.

The speed of the ship is different under different traffic flows. Through an analysis of the traffic flow data of ships in the linked control waters from September to October 2018, the downstream ship speed is mostly between 10–20 km/h and the upstream ship speed is mostly between 4-10 km/h. By fitting the speed data of ships in the linked control waters, the speed distribution of inland river ships conforms to a normal distribution, and thus the ship speed generated in the simulation model obeys the normal distribution. The ship speed data of Yunyang and Shishou are selected as examples, and Eq. (16) is used to fit the ship speed. The results are shown in **Fig. 12** and the specific parameters are listed in Table 2.

Table 2

Parameters generated during fitting of the ship speed.

	Downstream	Upstream
R-square	0.9873	0.9395
Standard deviation	1.904	1.051

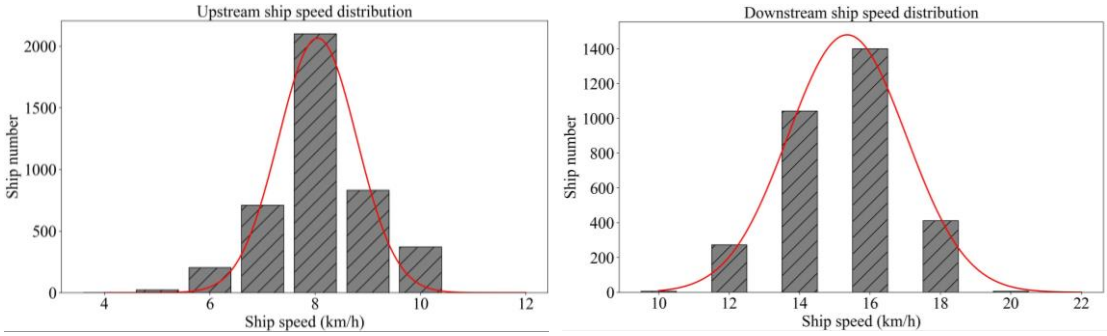


Fig. 12. Fitting of the ship distribution.

6.2 Parameter setting

According to the traffic flow characteristics of ships passing the lock in 2018, the ship generation rules in the simulation model are set, including ship type distribution, ship size distribution, speed change range, and other related parameters. The bearing capacity of the key nodes in the simulation model is set according to the distribution of anchorages and berthing areas along the water area under linkage control.

The channel is discretised according to specific information, such as the overall length and width of the linkage control segment and the rules of the CA. The total length of the channel is approximately 541 km, the average channel width is approximately 75 m, and the length of the ship is approximately 100 m. If the size of one cell in the cell space is determined to be 100 m × 100 m, the entire channel is divided into 5,410 cells. According to the specific situation of the Yangtze River waterway and the setting of ship berthing areas, the entire cellular space is divided into three parts: the regions above the Three Gorges Dam, between the Three Gorges Dam and the Gezhouba Dam, and below the Gezhouba Dam. The cellular space above the Three Gorges Dam is subdivided into four areas according to the location of each anchorage. The cellular space below the Gezhouba Dam is subdivided into four areas according to the location of each anchorage, as listed in Tables 3 and 4.

Table 3

Upstream Channel Discretisation.

Segment	Remote waters	Dispatch waters	Control waters	Near-dam waters	Core waters
Cell number	1230	460	600	170	380

Table 4

Downstream Channel Discretisation.

Segment	Near-dam waters	Control waters	Dispatch waters	Remote waters
Cell number	220	420	870	1060

In the anchorage setting, the simulation of the entire channel will encapsulate the anchorage cell of the same segment, and the reference to the capacity of anchorage everywhere will represent the location of the cell setting of the anchorage multi-agent as well as the capacity, as listed in Tables 5 and 6.

Table 5

Upstream Anchorage capacity.

Location	Dispatch waters	Control waters	Near-dam waters	Core waters

Dry season	420	70	80	220
Flood season	420	120	130	220

Table 6

Downstream Anchorage capacity.

Location	Core waters	Near-dam waters	Control waters	Dispatch waters
Dry season	170	130	350	395
Flood season	220	180	350	400

The simulation adopts a finite boundary, the simulation range of downstream ships is set from Yunyang to Three Gorges Dam, and the simulation range of upstream ships is set from Jingzhou to Gezhouba.

6.3 Model validation

To verify that the simulation model can truly reflect the actual navigation status of ships in linkage control waters, the actual traffic flow data were compared with the data derived from the simulation run. After the model ran steadily, the reliability of the model was verified in terms of the number of upstream and downstream ships arriving at the Yunyang Yangtze River Bridge and the Shishou Bridge and the number of ships passing through the Three Gorges Locks; the results are presented in Table 7 and **Fig. 13**.

Table 7

Verification of the number of arriving ships.

Type	Upstream	Downstream
Actual number of ship arrivals	4243	4145
Number of simulated ship arrivals	4348	4204
Error	105 (2.5%)	59(1.4%)

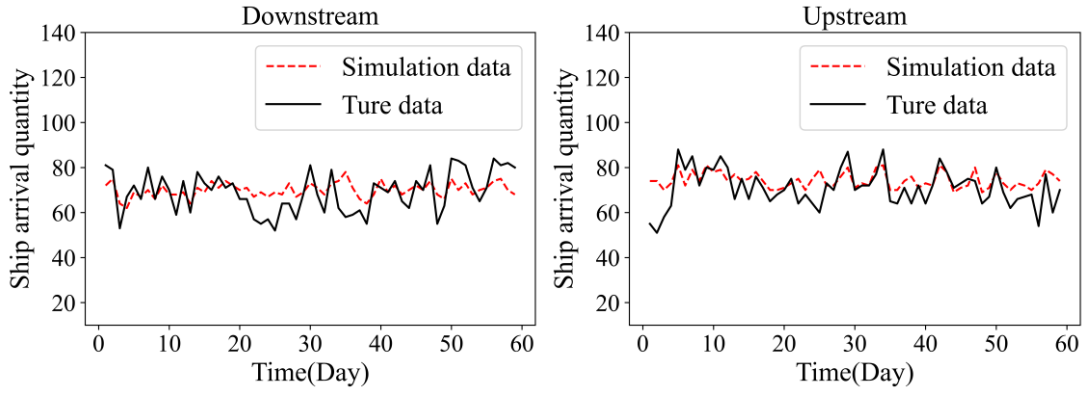


Fig. 13. Verification of the number of arriving ships.

Comparing the simulation results with the actual traffic flow data, it can be seen that the number of ships generated by the simulation is relatively stable, the actual number of ships is more random in the course of sailing, and some ships have some illegal behaviours such as non-compliance with navigation regulations, which changes the actual number of arriving ships significantly. From Table 7, the errors of the upstream and downstream ships are 2.5% and 1.4%,

respectively. Because inaccuracy is minimal, ship generation can be considered plausible.

Table 8

Verification of the number of ships passing through gates.

Type	Upstream	Downstream
Actual number of ships passing through ship lock	4172	4082
Simulation of the number of ships passing through the ship lock	3906	3793
Error	266 (6.4%)	289 (7.1%)

As can be seen from Table 8, during the 30-day simulation, the actual number of upstream ships passing through the ship lock was 4,172, the simulated number of ships passing through the ship lock was 3,906, with a relative error of 6.4%, the actual number of upstream ships passing through the ship lock was 4,082, and the simulated number of ships passing through the ship lock was 3,793, with a relative error of 7.1%. As there is a difference between the actual ship crossing behaviour and the abstract ship crossing behaviour in the simulation, the acceptable error was within 10%. Considering the environmental impact, driver behaviour and psychology, special circumstances, and other influencing factors in the actual sailing process, this model was considered to have high reliability and can accurately and truly reflect the navigation state of ships in the linked control waters.

6.4 Results and analysis

Based on the historical operation of the TGGD navigation system, we set up four scenarios in the simulation.

In Scenario 0, the linkage control scheme has not been implemented for the navigation system of the TGGD before 2017.

In Scenario 1, the linkage control scheme for the navigation system of the TGGD has been implemented. The period that is simulated is that after 2017.

In Scenario 2, the linkage control scheme of the TGGD navigation system has been implemented, and the ship traffic flow density further increases.

In Scenario 3, there is a change in anchorage capacity with the water level in the flood and dry seasons in the linkage control scheme area when the ship traffic flow density is further increased.

Table 9

Simulation Scenarios.

Scenario	Linkage control scheme	Change of traffic flow	Change of anchorage
Scenario 0：	-	-	-
Scenario 1：	√	-	-
Scenario 2：	√	√	-
Scenario 3：	√	√	√

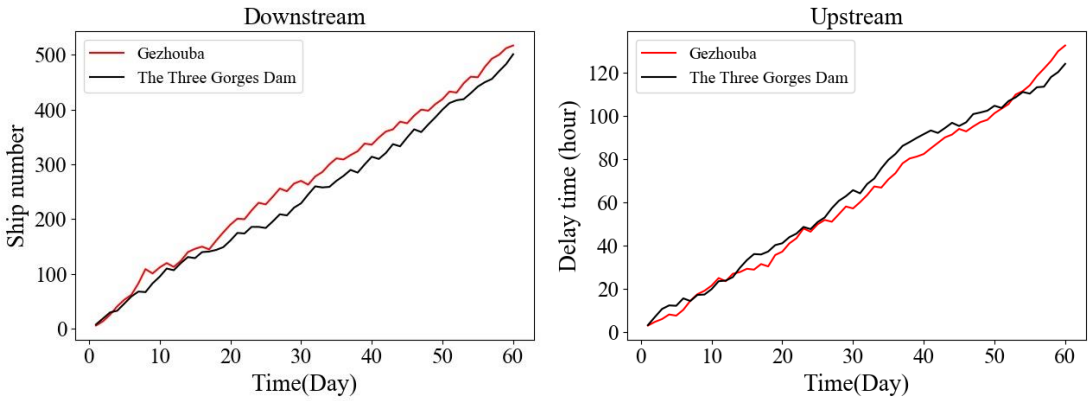


Fig. 14. States of a ship waiting to pass the lock.

According to the experimental results shown in **Fig. 14**, the situation of ship delay before the implementation of the linkage control scheme presents the following characteristics:

a. Ships crossing the lock sail directly to the core waters to wait for the lock. Over a period, too many ships arrive at the lock, causing channel blockage, and the ship-carrying capacity of the lock exceeds the navigation capacity of the hub.

b. The number of ships waiting to lock in the core waters fluctuates within a small range owing to the number of ships generated; however, owing to the traffic flow capacity and lock restrictions, the time and number of ships waiting to lock in front of the dam will continue to increase with time. After 60 days of simulation, the number of ships berthing and waiting for the gate reaches approximately 510, and the average waiting time reaches approximately 130 h.

c. All ships are overstocked in the waters in front of the dam prior to the implementation of the linkage control scheme, especially when the carrying capacity of the lock is reduced during the overhaul period and the carrying capacity of the waterway in the dry season. The problem of insufficient carrying capacity of the TGGD will be further highlighted.

As shown in **Fig. 15**, the ships arriving at dispatch water apply the linkage control scheme, obtain the relevant dispatching orders, and then wait in a timely manner in the anchorage and berthing areas. The ships waiting to pass through the gate typically exhibit the following characteristics:

1) The rate of saturation of the anchorage and mooring area along the route is inversely related to the distance from the core water region. The descending ships progressively stop at all berthing places along the way as the number of ships travelling through the lock continues to rise. The core water area is the first to reach saturation, and the farther away a water area from the core water area, the slower is its rate of saturation.

2) The capacity of each anchorage is positively related to the time that the downstream ships wait. The average wait time for ships leaving an anchorage increases with capacity. The number of ships waiting to be locked in the core waters decreased from 510 to 220 because of the implementation of the linkage control plan, and the average waiting period decreased from 130 h to roughly 65 h. The strain on the core waters significantly decreased as a result of the linking control scheme implementation, and the descending ships are now more organised.

3) The trend of the upstream ship waiting to pass the lock is the same as that of the downstream ship. The capacity of the berthing area causes each anchorage along the route to become saturated, and the average waiting time of ships at each anchorage is tied to that capacity. In particular, the downstream dispatch water anchorage is not saturated after 60 days of simulation running, and the average waiting time for ships in the anchorage did not reach the maximum value. In general, after the implementation of the linkage control plan, the berthing situation in the Gezhouba dam waters region has also been greatly eased, the number of waiting ships is greatly reduced, and the pressure

on on-site supervision and ship safety risks is reduced.

6.4.1 Scenario 1

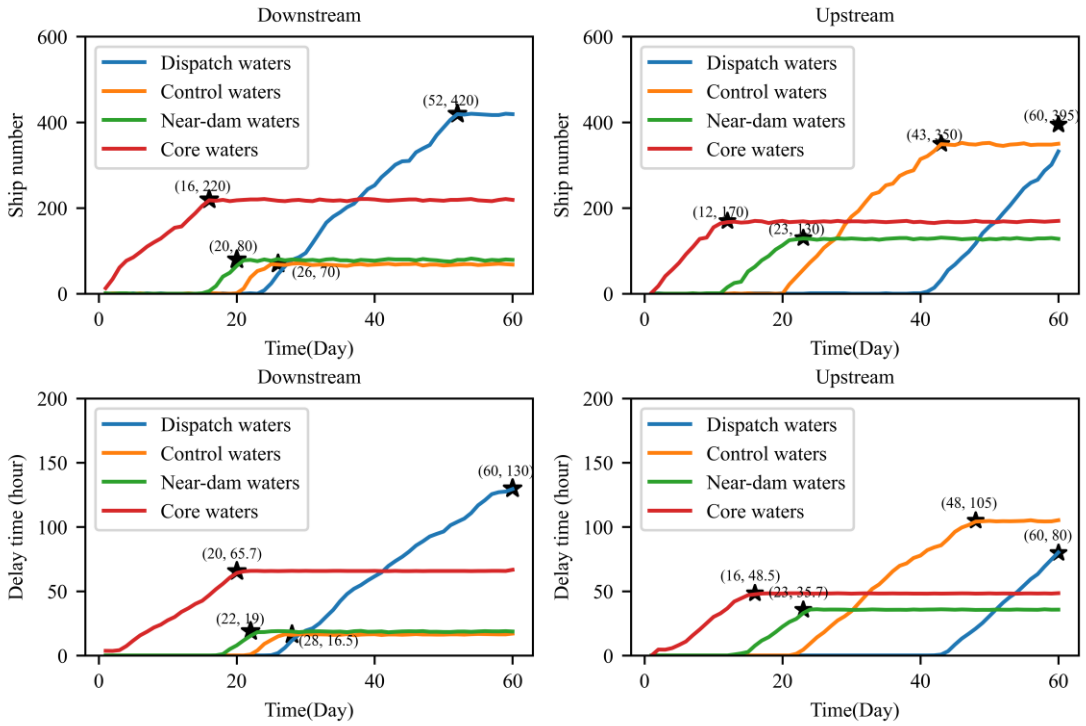


Fig. 15. Experimental result of Scenario 1.

6.4.2 Scenario 2

Increasing the demand for ships passing through locks increases the density of ships. According to the on-the-spot investigation and analysis of the traffic flow data of ships in the TGGD navigation system in recent years, the number of ships passing through the joint control waters is increasing annually, and the number of ships that passed through the lock in 2021 was increased by 9.29% year-on-year. It is predicted that the number of ships passing through the TGGD will increase steadily in the future. To study the situation of ships waiting for lockage in the berthing areas of each water area of the linkage control segment under the heavy lockage demand, we can convert the lockage demand of ships into the traffic flow of ships and adjust the ship generation parameters to increase the number of ships generated every day by 20% for the simulation.

When comparing the experimental results shown in **Fig. 16** with the initial results following the increased demand for ships transiting the locks, it was discovered that:

1) Because the capacity of the anchorage and berthing areas has not changed, increasing the demand for ships to pass the lock has little effect on the number of ships waiting to pass the lock when the berthing area of each voyage is saturated.

2) The start time of the ship backlog is affected by the distance between the anchorage and lock. The greater the distance, the greater is the impact on the backlog start time. The start time of the backlog of ships in the core waters was almost unchanged, and the start time of the backlog of ships in the waters near the dam was approximately eight days earlier. The mooring area in the dispatch waters is most affected by the change in the demand for ships to pass the gate, and the backlog of ships starts approximately 23 days earlier.

3) The anchorage in the originally unsaturated downstream dispatch water begins to operate at full capacity. The average layoff delay of ships waiting at anchorages is approximately 135 h.

Overall, the average waiting time of the ships in each berthing area increased to various degrees. It can be seen that the average waiting time of ships in the anchorage is affected by both the capacity of the anchorage and the demand for ships to pass through the lock.

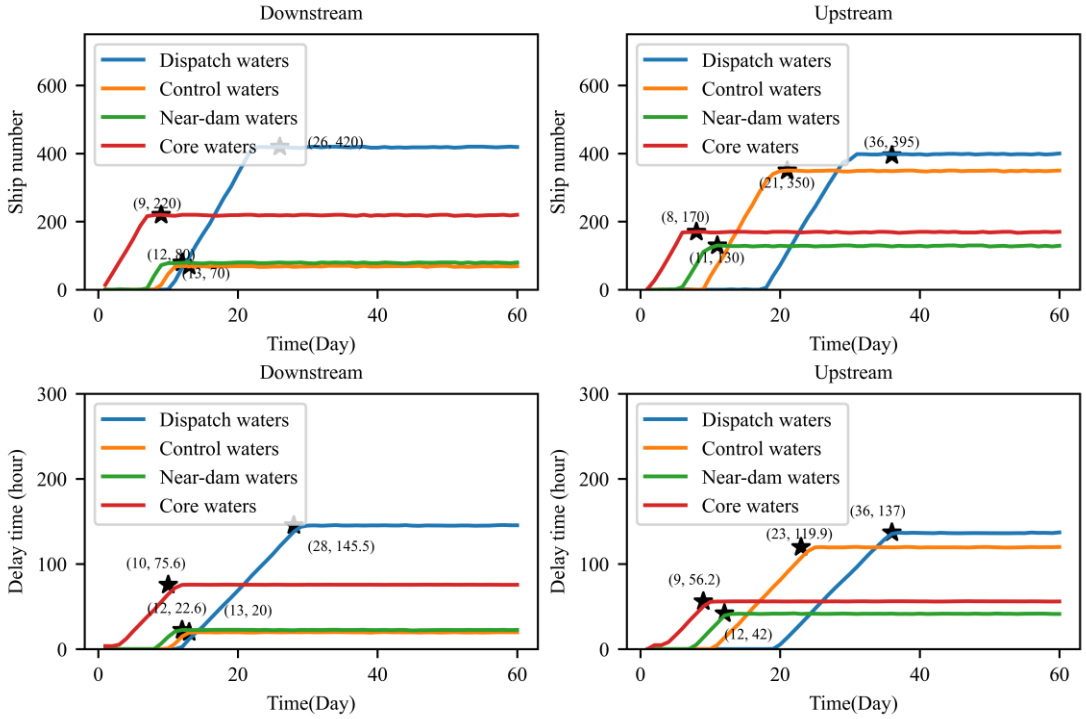


Fig. 16. Experimental results for Scenario 2.

6.4.3 Scenario 3

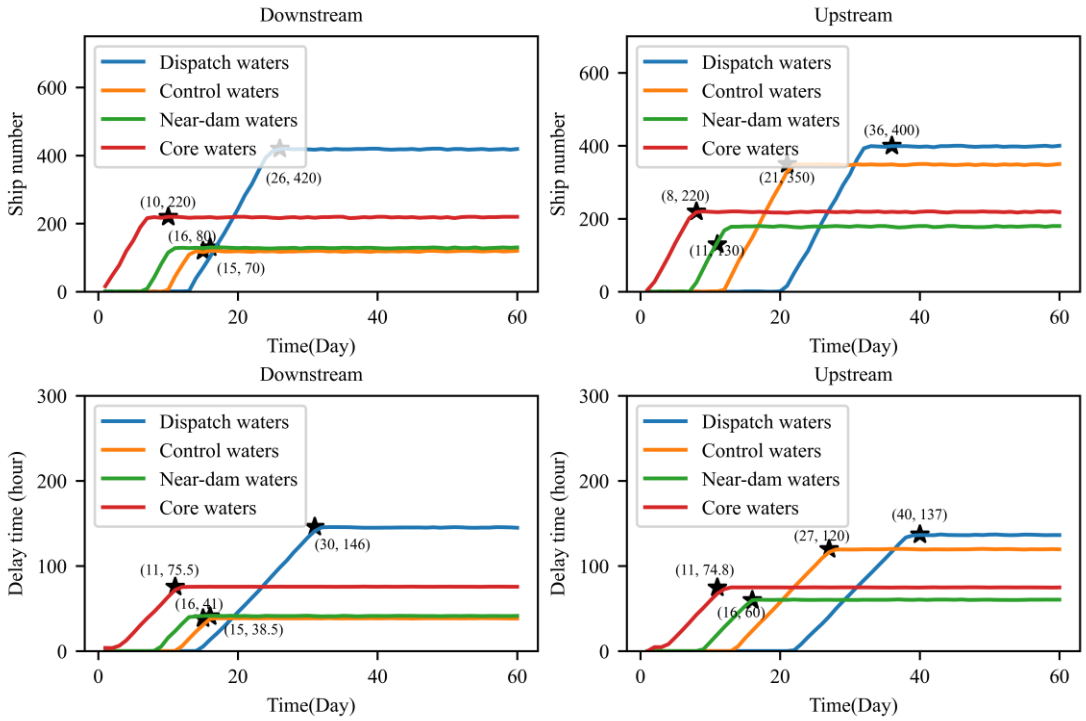


Fig. 17. Experimental results for Scenario 3.

From the simulation results shown in **Fig. 17**, it can be found that:

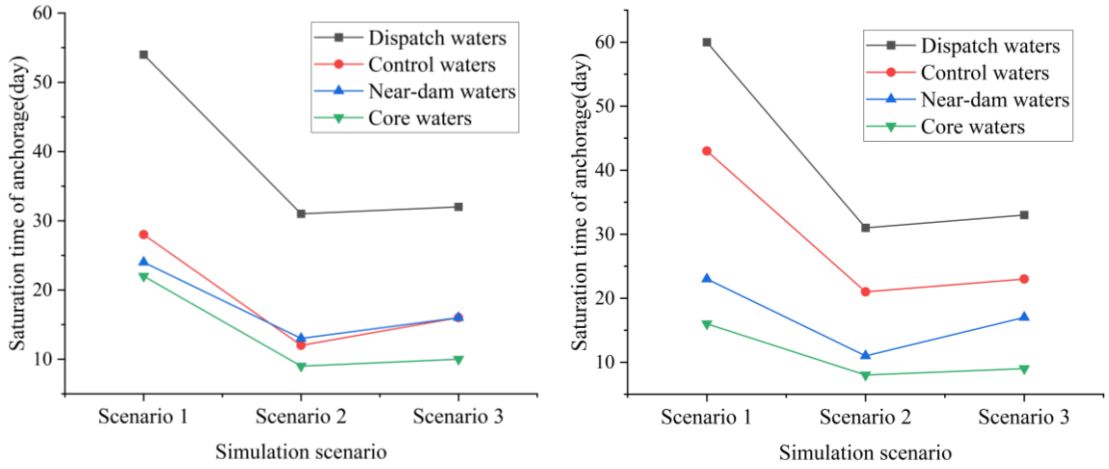
1) The start time of the backlog of ships will be slightly delayed, with an average delay of

approximately five days, in the upstream dispatch waters, downstream control waters, and dispatch waters. Therefore, the demand for anchorages along the routes that are operating at full capacity will be reduced by expanding the capacity of the selected anchorages.

2) The average waiting time of ships in the upstream Control waters increased from 20 h to approximately 39 h, the average waiting time of ships in the upstream Near-dam waters increased from approximately 23 h to 43 h, the average waiting time of ships in the downstream Near-dam waters anchorage increased from 42 h to 60 h, and the average waiting time of ships in the downstream Core waters increased from 56 h to 75 h, further verifying that the average watiting time of ships at each anchorage is positively correlated with the anchorage capacity.

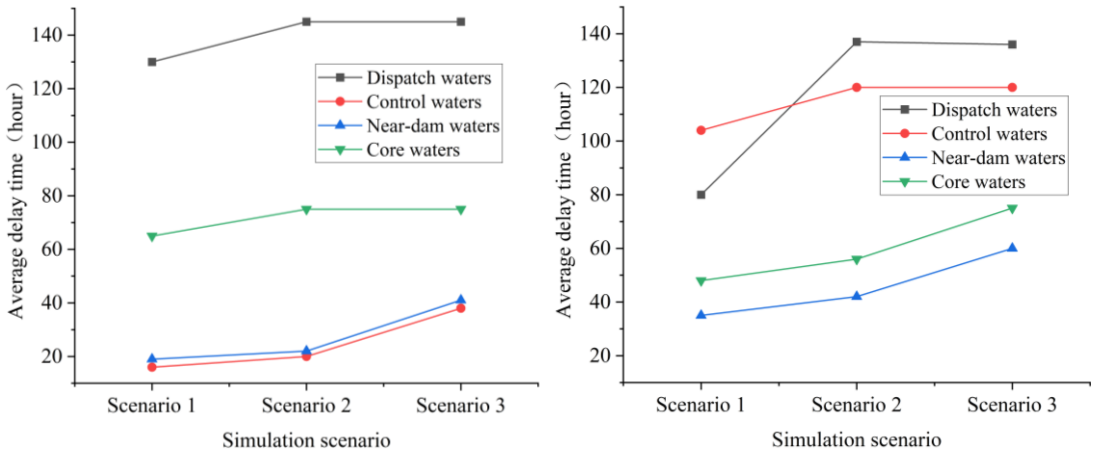
7. Discussion and conclusion

7.1 Discussion



a. Saturation time at anchorages above the Three Gorges

b. Saturation time of anchorage below Gezhouba Dam



c. Maximum delay time for downward ships

d. Maximum delay time for upward ships

Fig 18. Saturation times at anchorages and the maximum delay times.

The comparison and analysis of the outcomes before and after the adjustment reveal that while an increase in the number of ships and their delay times is a natural phenomenon (**Fig. 18**), it will lessen the backlog in the remote-controlled area. This is because of the increased anchorage in the waters near the dam and the dispatch waters. The specific performance is a delay at the beginning of the ship backlog and a reduction in the number of backlogged ships. Therefore, one of the steps

that can be implemented to reduce the backlog in remote waters is to increase the anchorage capacity in dispatch and near-dam waters.

After reviewing the experimental findings, we identified several issues with the linkage control strategy. Consequently, we provide a few optimisation ideas for the linkage control scheme for the administrative organisation by combining the trial results with the actual operation scenario.

Firstly, we discovered that the ship lock pass plan and the present security check plan of the TGGD are improvable. Currently, the Three Gorges Dam implements a 100% security check policy, which requires ships that do not pass the inspection to return to the anchorage for rectification. However, the vacant lock slots cannot be filled with new ships because the number of ships going to the security inspection area each day is the same as the number of lock slots available. This leads to a waste of lock resources. We believe there are some methods to alleviate this problem, such as arranging 10%-20% more ships to go to the inspection area each day to avoid waste, and this ratio can be dynamically adjusted based on the proportion of ships that did not pass the inspection the previous day. Additionally, improving the efficiency of security checks by using information technology can also help address this issue.

Secondly, our experiments revealed that under a certain ship traffic flow density, remote anchorages from the dam do not reach saturation. Consequently, overextending the water area range for linkage control is imprudent. However, water level changes affecting anchorage capacity necessitate expanding the linkage control water area range to alleviate ship waiting times. Thus, dynamic adjustment of water area ranges under linkage control is beneficial for managing varying traffic conditions.

7.2 Conclusion

In this study, a hybrid simulation modelling approach combining Cellular Automaton (CA) and Multi-Agent methods is proposed to analyse ship traffic through Waterway Transport Key Nodes (WTKNs). This approach employs CA to accurately simulate dynamic traffic on various waterways and utilizes multi-agent theory to manage anchorages effectively. The mathematical model developed is particularly adept at representing the critical role that key nodes play within the navigation system and their impact on navigation efficiency. By dynamically modelling the operational state with ships navigating through locks under diverse traffic schemes, our model offers insights into key operational conditions such as the maximum average waiting time at anchorages and saturation periods. Simulation results affirm that our model's capability to adjust anchorage capacities and water area ranges under linkage control effectively manages traffic conditions and fluctuations. This highlights the model's robust utility in enhancing decision-making for optimising traffic organisation at waterway transport key nodes.

This study presents a novel conceptual approach for analysing a large-scale, multi-key-node traffic system by simulating the traffic of a navigation system of this type for the first time, with a specific focus on ship traffic flow. Due to the modular structure of the proposed model, it can be adapted to different requirements, thus enabling its application in studying the traffic efficiency of other navigation systems with similar critical traffic nodes. Subsequent studies will further investigate the impact of individual ship behaviour on traffic efficiency and aim to enhance the accuracy of the model.

Acknowledgement

This study was supported by the National Natural Science Foundation of China (No. 51709219), Chinese Academy of Engineering and regional cooperation projects (No. HB2022B22), and Qingdao Research Institute of Wuhan University of Technology (No.:2019A02).

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